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Mitigating the Impacts of Development Corridors on Biodiversity: A Global Review

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Development corridors are extensive, often transnational and linear, geographical areas targeted for investment to help achieve sustainable development. They often comprise the creation of hard infrastructure (i.e., physical structures) and soft infrastructure (i.e., policies, plans, and programmes) involving a variety of actors. They are globally widespread, and likely to be a significant driver of habitat loss. Here, we describe the development corridors phenomenon from a biodiversity perspective and identify the elements of best practice in biodiversity impact mitigation. We use these to carry out a review of the peer reviewed literature on corridors to respond to three questions: (i) how impacts on biodiversity and ecosystem services are assessed; (ii) what mitigation measures are discussed to manage these impacts; and (iii) to what extent do these measures approximate to best practice. We found that of 271 publications on development corridors across all continents (except for Antarctica) mentioning biodiversity or ecosystem services, only 100 (37%) assessed impacts on biodiversity and 7 (3%) on ecosystem services. Importantly, only half of these (52, 19% of the total 271 articles) discussed mitigation measures to manage these impacts. These measures focused on avoidance and minimisation and there was scant mention of restoration or ecological compensation illustrating a deficient application of the mitigation hierarchy. We conclude that the academic literature on corridors does not give sufficient consideration to comprehensive mitigation of biodiversity impacts. To change this, impact assessment research needs to acknowledge the complexity of such multi-project and multi-stakeholder initiatives, quantify biodiversity losses due to the full suite of their potential direct, indirect and cumulative impacts, and follow all the steps of the mitigation hierarchy impact framework. We suggest a series of research avenues and policy recommendations to improve impact assessments of corridors towards achieving better biodiversity outcomes.

Keywords: development corridors, infrastructure corridors, mitigation hierarchy, economic corridors, biodiversity mitigation, impact assesment, strategic environmental assessment, environmental impact assessement

INTRODUCTION

Infrastructure, Biodiversity, and the Sustainable Development Goals

In 2015, all United Nations member states agreed to the 2030 Agenda for Sustainable Development (United Nations, 2015). The Agenda proposes 17 Sustainable Development Goals (SDGs) and 169 indicators to realise its vision of a prosperous and peaceful planet for people and nature. Goal 9 calls to "build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation." The term infrastructure refers to the facilities that allow humans to fulfil the need for energy (e.g., coal, wind, gas, solar, hydropower, waves, power lines, oil, and gas pipelines), water (e.g., canals, dams, pipelines), transport (e.g., ports, roads, railways), and telecommunications (e.g., internet cables) (Woetzel et al., 2016). Infrastructure development is considered a fundamental requirement to help achieve other SDGs (The Economist Intelligence Unit, 2019). Similarly, environmental goals underpin societal and economic goals (Folke et al., 2016)—as supported by the latest Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services global assessment report (IPBES, 2019), UN Convention on Biological Diversity (Romanelli et al., 2015; Secretariat of the Convention on Biological Diversity, 2020), and UN Food and Agricultural Organisation (FAO, 2019). Balancing infrastructure development and biodiversity conservation goals is therefore central to achieve sustainable development, but also involves socio-economic and political choices on how land is used, with likely trade-offs with other objectives.

What Is a Development Corridor?

The current and ongoing global expansion in infrastructure development has been described as an "infrastructure tsunami" (Laurance, 2010) or a "global infrastructure boom" (zu Ermgassen et al., 2019b). When these infrastructure projects are implemented, usually under a spatially oriented and economic development strategy, they are referred to as "development," "resource," "economic," or "growth" corridors (Nogales, 2014; Hope and Cox, 2015; Laurance et al., 2015; Reeg, 2017; Schindler and Kanai, 2019). Notable examples are the 33 corridors in Africa potentially crossing 400 protected areas (Laurance et al., 2015), or initiatives in Latin America, Asia, Europe, and Oceania (Nogales, 2014; Hope and Cox, 2015; Reeg, 2017; Sloan et al., 2019a). The Belt and Road Initiative is an example of this concept being taken to a global scale: a Chinese economic and political programme which was launched in 2013, comprising at least six interconnected corridors across the land and sea and over 15 countries in Asia and Europe (The Belt and Road Initiative, 2019), and has now has expanded to 140 countries including Sub-Saharan Africa, Latin America, and the Caribbean (The Green Belt and Road Initiative Center, 2021).

Although the term "Development corridor" has been often used as an umbrella term for these initiatives (Mulenga, 2013; Laurance et al., 2017; Enns, 2018; Collinson et al., 2019; Dong et al., 2019; Heinicke et al., 2019; Sloan et al., 2019b; Müller-Mahn, 2020), corridor terminology is diverse, not standardised, and it depends on the purpose of the corridor, the actors involved, and the stage at which it is. As such there are transport, trade, utility, agricultural, or resource corridors, among others (Nogales, 2014; Hope and Cox, 2015; The Development Corridors Partnership, 2021). Although they may start as such, in the long term these are not individual isolated projects. They usually comprise several infrastructure projects that serve to link growth nodes or anchor projects with urban centres, markets and/or points of imports and exports, such as ports. Mulenga (2013) uses the terms development corridors and economic corridors interchangeably as "the concept of using transport corridors as a means to develop the regions around the corridors." Hope and Cox (2015) propose planning development corridor as a systematic process which may start with a transport corridor but then evolves into a more complex economic corridor as different infrastructure, programmes, plans, and policies are incorporated. Nogales (2014) agrees, but employs the term "growth corridor" and proposes to use Spatial Development Initiates (SDI) as an umbrella term for all types of corridors (i.e., an agglomeration of economic activity in a specific location where businesses gain advantages through co-location; see Reeg, 2017). Therefore, crucially, development corridors are not static entities but rather a process which evolves towards a coordinated spatial development strategy with multiple stages—each involving different objectives and stakeholders.

Here we define development corridors as large, often transnational and linear, geographical areas targeted for investment under a spatially oriented and common economic strategy towards achieving long-term sustainable development. To avoid confusion, in this article we use the term "development corridors" to refer to all corridors, but we recognise and reflect on the varied terminology and complex nature of these initiatives (see **Box 1**).

We propose four broad ideal stages that should be common to all development corridors: concept planning, approval, implementation, and monitoring, and evaluation (**Box 1** and **Figure 1A**). In addition to these four stages, development corridors tend to evolve from simpler initiatives to a spectrum of different types of more complex development corridors (Nogales, 2014; Hope and Cox, 2015; Reeg, 2017). For example, a road or railway connecting key cities or trade hubs to resources is initially considered as a transport corridor and, as hard and soft infrastructure are created and other economic and non-economic dimensions are integrated into the system, it can evolve into a logistics corridor, and economic corridor or true development corridor (**Box 1** and **Figure 1B**).

Best Practice in Biodiversity Impact Mitigation

The most widely used tool to assess and mitigate the impacts of development activities on the environment at a project level is Environmental Impact Assessment (EIA), adopted as a national legal instrument by 180 countries and territories (Craik, 2019). At the strategic planning level, at least 40 countries had Strategic Environmental Assessment (SEA) legislation in place (UNEP, 2018). The scope of an SEA is broader than that of an EIA and refers to "a range of analytical and participatory approaches that aim to integrate environmental considerations into policies,

BOX 1 | Key phases and evolution of development corridors.

1. Concept planning: The aim of concept planning is to determine whether the proposed development corridor in a country or region is economically, social and environmentally viable, which is often led by government agencies and financial institutions. When an agreement is reached, feasibility and scoping studies are conducted, key initial projects are identified, initial stakeholder consultations take place, and key initial investments are secured, ideally conducted under a SEA framework. Here, risks and potential significant biodiversity impacts should be identified, and plans made for minimisation, restoration, and compensation. The most important mitigation strategy in this phase is avoidance. Concept planning is finalised when the development corridor initiative is approved.

2. Approval: Approval to undertake the initiative occurs when assessments (e.g., scoping, feasibility, EIA, SEA reports) and plans developed in the first phase should be scrutinised for compliance with legal and lender requirements. If some changes are required, the process could come back to phase one (concept planning). If the initiative is not approved the process ends or is put on hold.

3. Construction and implementation: Implementation involves the construction of the development corridor. Ideally this phase is coordinated by designated authorities which could be a new or an existing institution (e.g., Lamu Port, South Sudan, Ethiopia Transport corridor (LAPSSET) is coordinated by the LAPSSET authority). Agreed design and plans are implemented through hard and soft infrastructure supported by further investment. Hard infrastructure refers to several physical projects that compose the corridor, implemented sequentially or at different times (e.g., a road to a mined area, a dam, or railway). Each individual project will require an EIA according to the law in the country where it is proposed, with its own phases: from conception, design, execution, operation, and upgrade or closure or decommission (CSBI, 2013). Soft infrastructure refers to the policies, regulations, partnerships and collaborations that need to be put in place to facilitate implementation of the development corridor. The implementation phase is typically when the majority of beneficial and detrimental impacts on biodiversity actually occur, but not necessarily when they can be mitigated. Rather, phases 1 and 2 represent the best opportunities for impact avoidance. Implementation may last for many years or constantly evolve as some operational projects are decommissioned or closed, others are expanded or upgraded, or new projects are proposed and developed. The most important mitigation strategies during implementation are avoidance and minimisation, and in this phase, restoration and compensation measures commence.

4. Monitoring and evaluation: This phase involves tracking the economic, social, and environmental performance of the development corridor and its individual projects through the indicators identified in previous phases. Evidence of positive and negative impacts are documented as in post development audits. Monitoring and evaluation should be led by designated corridor authorities and lenders and government agencies of individual projects and it should start with implementation. Most significant impacts have occurred or are ongoing and monitoring of minimisation measures are place. It is in this phase when it can be assessed how well the predictions and recommended management measures perform in practice and ideally apply the necessary corrections. The main mitigation strategies here are restoration and compensation.

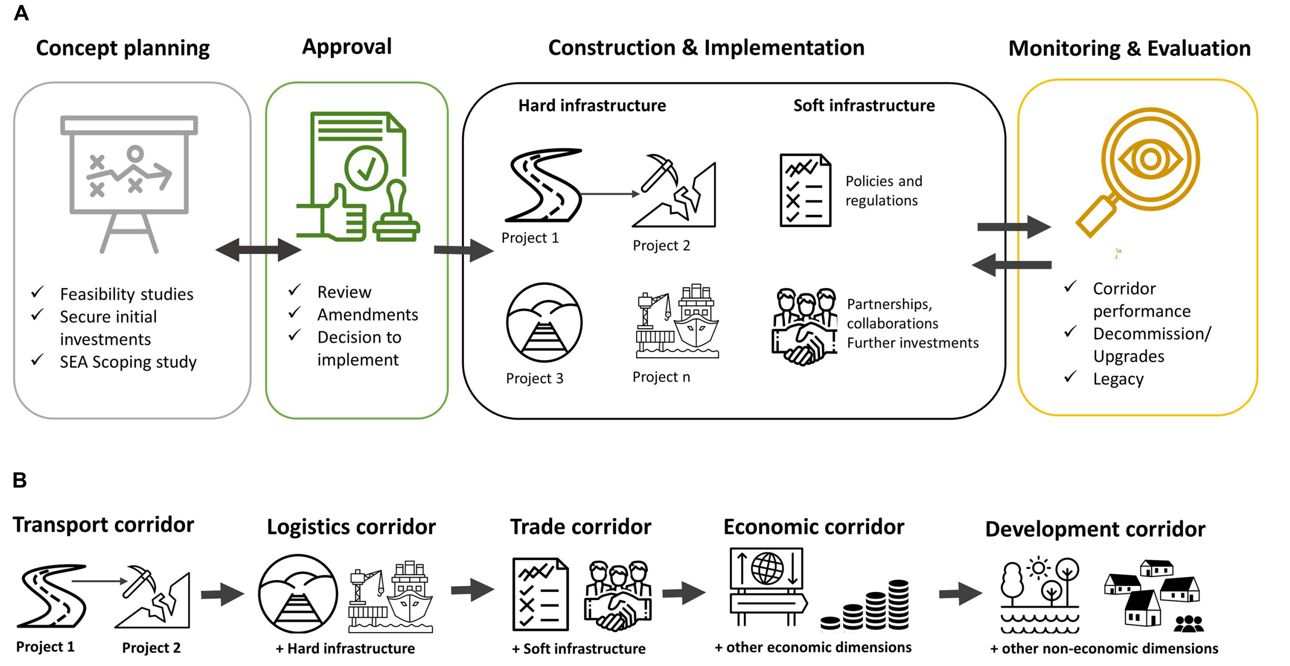

FIGURE 1 | (A) Main phases of a development corridor. Each individual project in the construction and implementation phase will have its own project cycle phases (i.e., conception, design, execution, operation, upgrade, closure, or decommission). Specific project level surveys, baseline assessments, feasibility studies, and EIA are conducted for each of those projects following the laws and regulations of the countries where they are implemented and complying with the standards and procedures required by lenders. **(B)** A simplified example on how a transport corridor may evolve to a development corridor as hard and soft infrastructure and other economic and non-economic dimensions are incorporated (adapted from Nogales, 2014 and Hope and Cox, 2015). **(A)** Attributions for icons. Concept planning: created by jokokerto; Approval: created by Template; Road: Created by art shop; Mining: created by Hamed; Port: Created by ATOM; Railway: created by Sedlac; Policies & Regulations: created by Becris; Partnerships and collaboration: created by Priyanka; Monitoring & evaluation: created by JunGSa. **(B)** Attributions for icons. Road: Created by art shop; Mining: created by Hamed; Railway: created by Sedlac; Port: Created by ATOM; Policies & Regulations: created by Becris; Partnerships and collaboration: created by Priyanka; Trading: created by Made; Investment: created by gilbert bages; Ecosystem: created by Made x Made; Village: created by Martina Krasnayova; People: created by Support Designs.

plans and programmes and evaluate the interlinkages with economic and social considerations" (OECD, 2006). SEAs are thus more directly relevant to development corridors although each individual project within a corridor will need to have an EIA mandated by local regulations.

In addition to what is required by national law, the use of decision-making frameworks is becoming mainstreamed in policy for governments, lender, and multinational corporations. One such framework is the mitigation hierarchy, which guides the management of biodiversity and people impacts from development (CSBI & TBC, 2013; Bigard et al., 2017), supports corporate commitments to achieve no net loss, or net gain of biodiversity in projects' lifecycles or commodity production (Bull and Strange, 2018; de Silva et al., 2019). Achieving no net loss for biodiversity means that the implementation of a project has not resulted in net biodiversity loss in comparison to an established baseline or counterfactual. Net gain proposes going even further so that new biodiversity is created through the life cycle of the project. The mitigation hierarchy is central to achieve these objectives and ultimately seen as a path towards better outcomes for biodiversity and people (Arlidge et al., 2018; Griffiths et al., 2019; Jones et al., 2019; Bull et al., 2020; Maron et al., 2020). It proposes four sequential but iterative stages, typically phrased as: avoid, minimise, restore, and offset. Avoid and minimise are preventive actions which focus on anticipating and preventing an impact, while restore and ecological compensation are remediative actions which aim to repair existing impacts (CSBI & TBC, 2013).

More importantly, over the past decades financial institutions have developed environmental and social performance standards, aimed to minimise the risks and maximise opportunities of their investments, some of which specifically address impacts on biodiversity and ecosystem services. A well-recognised example of such a standard is the International Finance Corporation Performance Standard 6 or IFC PS6 (IFC, 2012). To provide funding, the IFC PS6 requires that projects should assess direct impacts (direct footprint of a project), indirect impacts (not directly attributed to a project but caused indirectly by the project), and cumulative impacts (interactions between other projects in the landscape plus other external pressures) on biodiversity (IFC, 2013). IFC PS6 then requires impact mitigation measures to be put in place, such that the net outcome is no net loss and net gain for biodiversity to be achieved (IFC, 2012). PS6 is seen as an example of best practice in biodiversity impact mitigation (Narain et al., 2020). However, a study on best-practice on biodiversity safeguards for the Belt and Road Initiative's financiers revealed that most associated lenders do not follow such best practice (Narain et al., 2020). Moreover, there is no consensus around common standards and sustainability metrics for infrastructure development, as shown in a review of 12 sustainability standards for financing infrastructure (Bennon and Sharma, 2018).

The impacts on biodiversity from the proliferation of development corridors have been highlighted for the African continent (Laurance et al., 2015), Indonesia (Sloan et al., 2019a), Papua New Guinea (Sloan et al., 2019b), and the Belt and Road Initiative (Ascensão et al., 2018; Hughes, 2019), among others, revealing significant risks for biodiversity conservation in the long-term. Although fundamentally important in raising awareness, such studies scarcely detail which methods and approaches are being used or proposed to assess impacts of these developments and recommendations on specific mitigation measures. More importantly, it is not clear the extent to which existing research on development corridors follows best practice frameworks and tools mentioned above, despite them becoming mainstream in sustainability standards and corporate commitments. Given the wide geographic scope, the global proliferation of these initiatives, and their particular complexity (i.e., many ongoing projects and numerous stakeholders involved), there is a need to better understand how they develop and, more importantly, how impacts they have on biodiversity and ecosystem services (if any) are being assessed and managed.

Here, we describe corridors from a biodiversity perspective and identify the elements of best practice in biodiversity impact mitigation, considering related ecosystem services where possible. We focus on the specific nature of these complex initiatives acknowledging that the science to understand and manage the impacts of individual infrastructure projects has many years of history (Spellerberg and Morrison, 1998) and is well-advanced, especially for roads (Coffin, 2007; Fahrig and Rytwinski, 2009; van der Ree et al., 2011; Forman et al., 2015; Bennett, 2017; Collinson et al., 2019) but also railways (Barrientos et al., 2017, 2019). Here we are particularly interested in development corridors more broadly and how impacts on biodiversity are assessed and what mitigation measures (if any) are proposed. Applying a Rapid Evidence Assessment of peer-reviewed publications on corridors and biodiversity impact mitigation, we therefore aim to: (i) understand how impacts on biodiversity and ecosystem services are assessed; (ii) document the mitigation measures proposed to manage these impacts; and (iii) assess how these approximate to best practice. We then discuss key gaps identified, explore alternatives to fill these with existing tools and approaches, and put forward policy relevant recommendations.

METHODS

We carried out a Rapid Evidence Assessment (Collins et al., 2015) to compile academic articles that assessed impacts of biodiversity and ecosystem services from the specific case of corridors. Whether approved impact assessments linked to existing corridors followed best practice was out of the scope of this study. There is evidence that formal impact assessments often lack enough detail on biodiversity impact mitigation (Bigard et al., 2017; Simmonds et al., 2020) and specific guidance to better integrate biodiversity into impact assessment has been developed to fill in this gap (Secretariat of the Convention on Biological Diversity and Netherlands Commission for Environmental Assessment, 2006).

The review was conducted following three main steps (**Figure 2**): (i) use of specific search terms in the title, abstract, or key words to find relevant articles in the Scopus and Web of

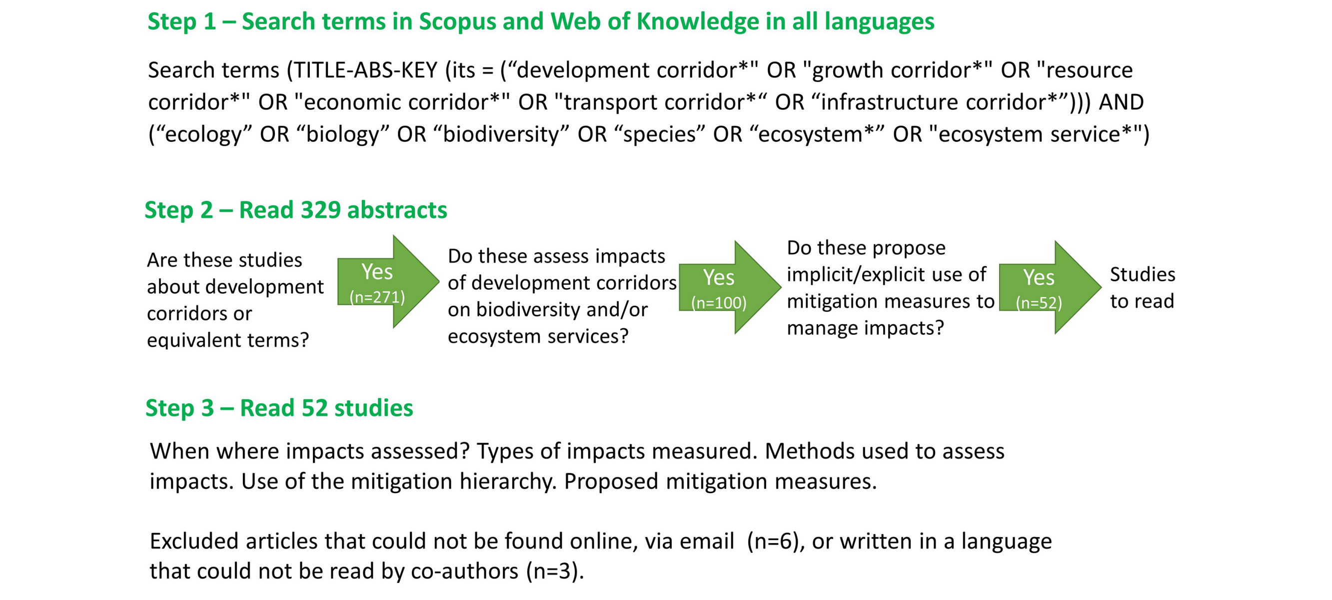

FIGURE 2 | Steps of rapid evidence review including search terms, screening and inclusion and exclusion criteria.

Knowledge Core Collection databases in all languages from when records are available up to December 2020; (ii) apply inclusion and exclusion criteria to all titles and abstracts found; and (iii) code full articles included in the review.

The search terms were related to corridors terminology with a focus on biodiversity and ecosystem services (Step 1). The most commonly used terms were compiled from expert opinion through 3 years of work in the Development Corridors Partnership project between 2018 and 2020 (DCP, 2021). The results from Scopus (n = 347) and Web of Knowledge (n = 82) were combined to eliminate duplicates (n = 329) and screened at title and abstract level for three inclusion criteria (**Figure 2**, Step 2). Our search did not capture impact assessment studies of individual projects, because our interest was to find studies considering the specific nature of corridors not individual projects within them. However, we acknowledge these studies might have applied best practice. We address this gap in the discussion by identifying other methodological approaches not yet applied to corridors specifically but that could prove useful in this context. We excluded articles that: were not about development corridors (i.e., despite using similar terms, such as transport corridors of sediments or develop greenways for sustainable urban transport); or where corridors were not the primary focus of the research (**Figure 2**).

For studies included in the review, we extracted data on the country, countries, or regions (i.e., more than one country included in the same article) of the corridors studied, stage of the corridor addressed, metrics used to measure biodiversity and ecosystem services, and methodological aspects related to best practice in impact mitigation outlined in **Table 1**. In this step we excluded articles that could not be found to be read due to not being accessible online, and those written in a language that could not be read by the authors.

RESULTS

We found 271 articles about development corridors published from 1971 to 2020, 73% in the past 5 years. Of these, 196 articles studying one specific development corridor and 75 looking at multiple corridors. In total 94 individual corridors were studied across all articles. The term economic corridors, was the most used, followed by transport corridors and development corridors (**Figure 3**). Other terms used in the articles included growth corridor tourism corridor, infrastructure corridor, and to a less extent scenic conservation corridor, resource corridor, and agricultural corridor.

Of the 271 articles, 189 were country level analyses and 82 transnational level (more than one country) studies. The geographic focus was biased towards Asia (n = 127, 47%), followed by Africa (n = 40, 15%), Europe (n = 29, 16%), and then Oceania and North America with 7 and 5%, respectively (**Figure 3**). There were two studies in Central America, one in Costa Rica and one regional, and no studies in South America. Over 70% of the studies were country specific (n = 189, 72%), covering a total of 45 countries (**Figure 4**) while 30% took a regional approach. The country with the most articles was Pakistan (n = 46) followed by Australia with 15 and Russia and Tanzania with 11 each. All of the Pakistan case studies were about the Belt and Road Initiative, which in total was the focus of 25% of the studies (n = 68).

Assessment of Impacts on Biodiversity and Ecosystem Services

Of the included 271 articles, 37% (n = 100) assessed the impacts of corridors on biodiversity but only seven assessed impacts on ecosystem services. Thirty-seven per cent (n = 37) of assessments

TABLE 1 | Methodological aspects of biodiversity mitigation evaluated for studies screened at full text level.

Coded variables	Best practice recommendation	Definitions and scope of assessment
When were impacts assessed	Assess potential impacts in early stages of development to avoid significant impacts before the projects start.	• Stage of corridor when impacts were assessed (**Figure 1A**) • Assessment completed before (*ex ante*) or after (*ex post*) construction of a project within a corridor.
Types of impacts measured	Account for all potential direct, indirect, and cumulative impacts associated to development.	We searched for three types of impacts on biodiversity (BBOP, 2018): • Direct impacts: impact directly attributable to a defined action or project activity (e.g., a road) • Indirect impacts: impacts triggered in response to the presence of a project, rather than being directly caused by the project's own operations (e.g., habitat loss due to population increase caused by the presence of the road). • Cumulative impacts: total combined impact arising from another project (under the control of the developer); other activities (that may be under the control of others, including other developers, local communities, government), and other background pressures and trends which may be unregulated (e.g., other roads, other causes of population growth resulting in additional impacts, climate change impacts, etc.).
Methods used to assess impacts	Select appropriate metrics to account for all biodiversity losses due to development, including assessments of biodiversity extent and condition.	• Metrics used to measure biodiversity impacts. • Use of geographically referenced data and/or spatial analyses tools to assess impacts. • Techniques and combinatorial tools used to assess impacts for spatial and non-spatial analyses (e.g., modeling, buffer overlaps, field data collection, stakeholder surveys).
Use of the mitigation hierarchy	Follow all phases of the mitigation hierarchy (avoid, minimise or reduce, restore or rehabilitate, offset or compensate) to manage impacts of development and aim for no net loss or net gain of key biodiversity.	• Explicit use**:** publications mentioning or using the mitigation hierarchy as a framework to manage impacts. • Implicit use: publications mentioning phases of the mitigation hierarchy and/or actions that equal to mitigation hierarchy actions. • No mention of the mitigation hierarchy
Proposed mitigation measures	Consider existing biodiversity impact mitigation policies and develop strategies and action plans focusing on priority biodiversity elements and identify specific management actions. Monitor performance and impacts and do adaptive management.	• General to specific measures proposed to manage impacts on biodiversity. • In which phases of the mitigation hierarchy were those measures proposed. • Proposed indicators to monitor impacts and mitigation management.

were conducted in the conception planning stage of a corridor (**Figure 3**). Of these 74% percent where country case studies across 33 countries (**Figure 4**). The reduction of studies assessing biodiversity or ecosystem services impacts from 271 to 100 articles was particularly prominent in Africa (75% reduction), Asia and Latin America (over 60% reduction each). The number of countries represented went down from 45 to 33.

Over half of studies used either ecosystems (37%) or species (25%) to measure impacts on biodiversity. Fewer publications (14%) used a mix of biodiversity metrics combining species, protected areas or other important conservation areas (e.g., Mahmoud et al., 2017; Laurance et al., n.d.; Sloan et al., 2019a). Notably, 14% of studies assessed impacts on the environment not using any specific quantitative metrics related to biodiversity. This includes measuring pollutants generated (Valentukevičiene and Ignatavičius, 2011) but not linking these to biodiversity impacts, or changes on different land uses over time which could or could not relate to biodiversity loss and degradation (Subasinghe et al., 2016). The three studies assessing impacts on ecosystem services were specifically on water quality (Valentukevičiene and Ignatavičius, 2011; Er et al., 2014) and carbon sequestration (Chen et al., 2017). There were four studies that used carbon emissions as an environmental impact metric but did not focus on ecosystem services.

Biodiversity Mitigation Measures in Corridors

Of the 100 studies assessing impacts on biodiversity and ecosystem services, 61 proposed mitigation measures. The studies that did not comply this inclusion criteria (**Figure 2**) only assessed trends or impacts of land use or biodiversity change but did not propose or discuss explicitly or implicitly any mitigation measures. In addition, we excluded studies that could not be found ($n = 6$), and those written in a language that could not be read by the authors ($n = 3$), leaving 52 studies to be fully read.

These final 52 studies account for 19% of the initial 271 studies on corridors. While the number of studies decreased, from 271 to 52, the geographical coverage remained similar with Europe as the second continent with more studies followed by Oceania and Africa (**Figure 4**). At a country level, case studies from 19 countries were excluded as they did not propose any mitigation measures leaving a total of 45 studies across 26 countries (**Figure 4**). 34 of these 52 publications used spatially explicit methods and modeling techniques were the most used (**Figure 5**). The modeling was used to assess impacts on ecosystems, species, land use or from invasive species. Seventeen studies used more simple techniques, such as assessing linear proximity and overlaps with the planned corridor footprint or overlaps with a buffer created around the corridor. Eleven

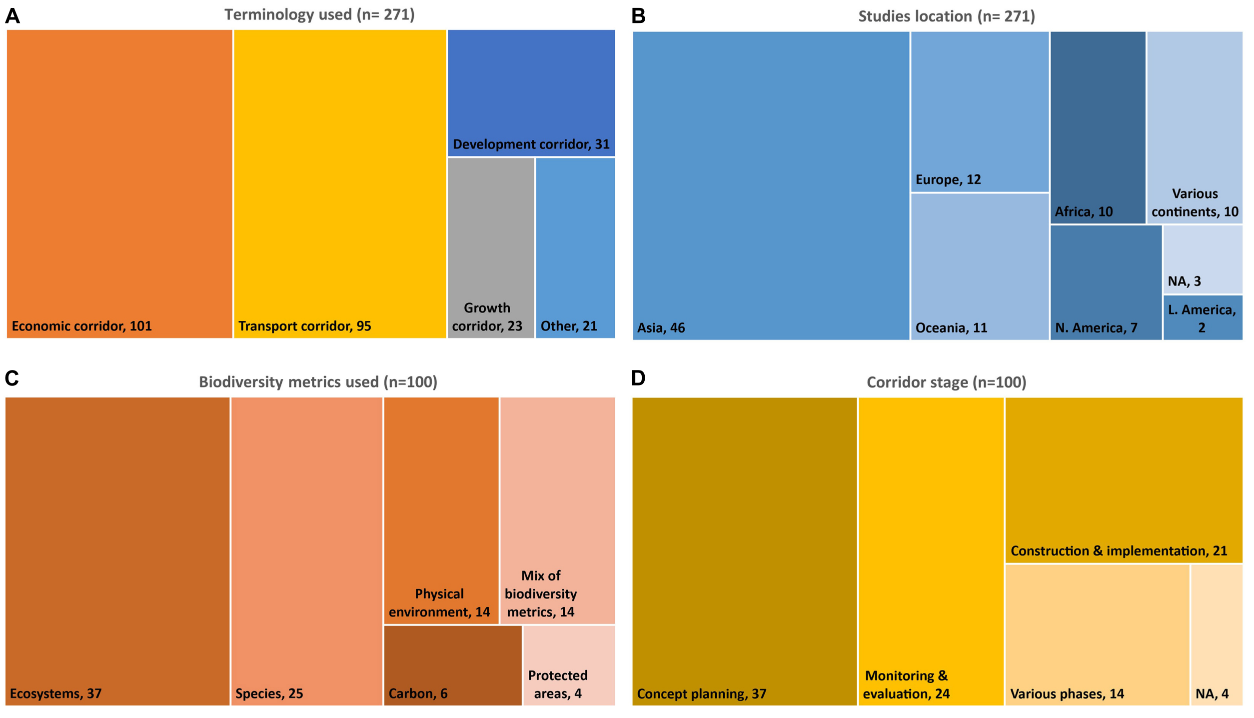

FIGURE 3 | Number of articles classified as **(A)** terminology used, **(B)** continental coverage, **(C)** metrics used, and **(D)** stage of corridor when assessment was conducted. *n* = 271 includes all abstracts that mentioned corridors in any of the search terms (Step 1). *n* = 100 includes abstracts where impacts on either biodiversity or ecosystem services were assessed (Step 2). NA = not applicable when the studies did not focus on a specific geographic location or when the corridor stage was not a consideration of the study.

studies based their impact assessment on data collected through field surveys. Non-spatial methods were qualitative assessments of impacts (10) and mainly reviews of existing research (3), with no actual quantification of impacts. Notably, two indicator prioritisation studies selected best indicators to monitor corridor performance (Zhang et al., 2017; Yogeswari and Bala Keerthana, 2019).

Sixty-two percent of the articles only assessed direct impacts on biodiversity. Those which assessed indirect impacts as well (37%) evaluated linear proximity or overlaps with buffers drawn from the main linear infrastructure of the corridor (Laurance et al., 2015; Mahmoud et al., 2017; Sloan et al., 2019b), by measuring land cover changes over time in the area of influence of the corridor (Petty et al., 2012; Villarreal et al., 2013; Wilson et al., 2013), or combining both (Heinicke et al., 2019).

The application of the mitigation hierarchy was explicitly mentioned in only two studies (Bastille-Rousseau et al., 2018; Heinicke et al., 2019). Similarly, we found no studies that assessed restoration or offsets alternatives for corridors nor any discussion or evaluation of no net loss or net gain achievement, although the existence of these approaches was briefly mentioned in some of them. There was, however, implicit use of the mitigation hierarchy in other studies proposing minimisation measures (56%) and avoidance (21%). The remaining 23% combined avoidance and minimisation measures. The main avoidance action proposed was to not develop infrastructure in important places for biodiversity (e.g., Laurance et al., 2015; Pomazkova et al., 2019). Regarding minimisation, most measures were species specific [e.g., moose (Wierzchowski et al., 2019), West African chimpanzees (Heinicke et al., 2019), elephants (Bastille-Rousseau et al., 2018), or invasive species (Liu et al., 2019)], while one study proposed minimisation measures for several species (Cserkész and Farkas, 2015). Only one study was found that assessed direct, indirect, and cumulative impacts (Lechner et al., 2017).

DISCUSSION

Key Evidence Gaps

We find three major evidence gaps. First, less than half (37%) of the peer reviewed literature on development corridors assess impacts on biodiversity and even less so (3%) on ecosystem services. Those studies that assess impacts on biodiversity do not follow best practice as defined in this review (**Table 1**) and only one in 5 (19%) propose mitigation measures to address those impacts. Second, the review found only one study in South America, 10 in Africa, and 11 in Oceania which assess impacts on biodiversity. These are continents with high levels of biodiversity and also where development corridors are expanding (Laurance et al., 2015; Sloan et al., 2019a,b; Vilela et al., 2020). Third, the lack of impact assessments on

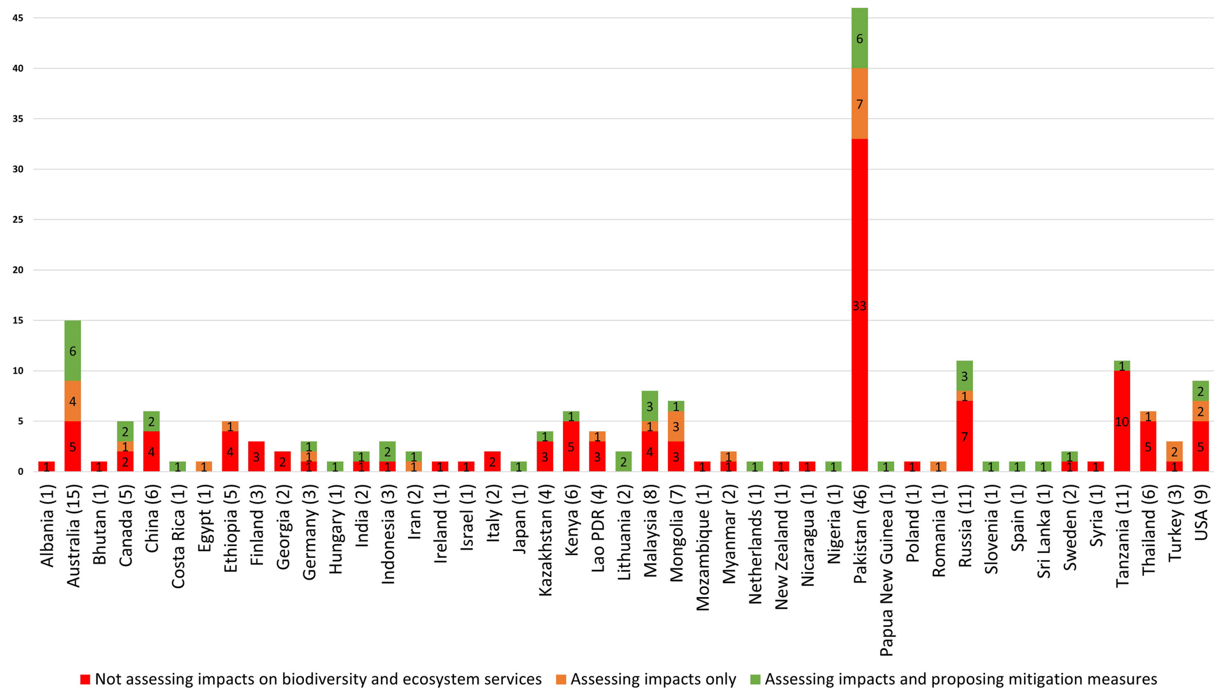

FIGURE 4 | All country case studies divided by: those not assessing impacts on biodiversity and ecosystem services (red); those assessing impacts on biodiversity and ecosystem services (orange); and those which in addition to assessing impacts and proposing biodiversity mitigation measures to manage those impacts (green). Total number of case studies are in brackets by the country name.

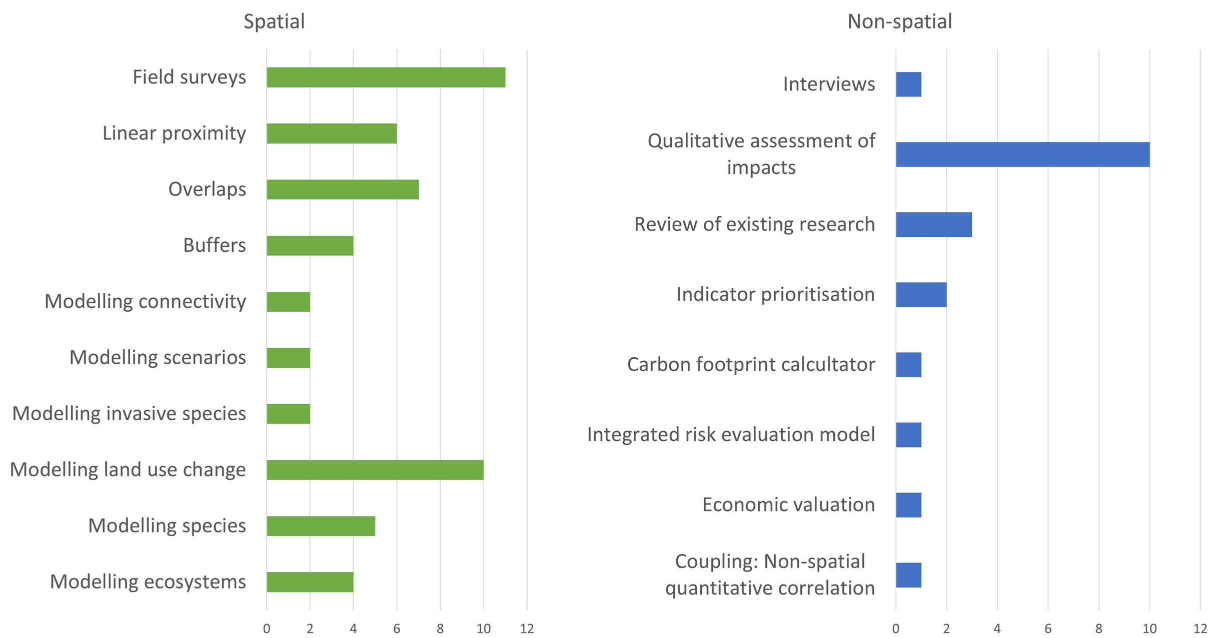

FIGURE 5 | Methods used to assess impacts on biodiversity for the 47 case studies. Some studies used more than one method.

ecosystem services suggests at best partial consideration of how development corridors might bring socio-economic benefits to local people. Moreover, there is evidence that infrastructure corridors can negatively impact ecosystem services (Mandle et al., 2015; Nyumba et al., 2021). In this discussion, we focus on impacts on biodiversity within development corridors from two perspectives: how impacts are assessed and how impact mitigation is approached.

How Biodiversity Impacts Are Assessed

Most studies in this review only assess direct impacts on biodiversity; indirect impact assessments were restricted to buffers or linear proximity analyses from the proposed development. There was only one specifically looking at cumulative impacts (Lechner et al., 2017). These findings align with Collinson et al. (2019) who, in a review on road ecology research in Africa, found that most publications examined the direct impacts of roads only and focused on single species assessments. Notably, there were only two publications specifically assessing the impacts of development corridors on ecological connectivity (Heinicke et al., 2019; Wierzchowski et al., 2019), despite that habitat fragmentation is one of the most well-established effects of infrastructure development (van der Ree et al., 2011; Barrientos et al., 2019), which often occurs in early stages of corridor construction.

Although the metrics used to measure impacts were diverse, very few studies did this in a systematic and comprehensive way, and one-fifth of studies did not use quantitative metrics to measure biodiversity loss. Quantitative metrics were restricted to areas of habitat loss or only assessing overlaps of proposed development projects without estimation of ecological degradation or condition. The latter is generally needed to account for all potential biodiversity losses due to development and to estimate potential gains through mitigation actions when alternative options are proposed. This misalignment on metrics used to assess impacts has been already identified as a gap in impact assessment in the context of biodiversity offset implementation (Marshall et al., 2020). Moreover, the lack of use of quantitative metrics seems to be a common issue in corporate reporting of biodiversity impacts which makes it difficult to assess whether mitigation measures work or positive outcomes for biodiversity can be achieved (Addison et al., 2019).

How Biodiversity Impact Mitigation Is Approached

Collinson et al. (2019) also found that only one-third of publications on impacts of roads on biodiversity provided recommendations for interventions to reduce or mitigate the impacts. Comparatively, in this review, only one-fifth (52 out of 271) of publications that assessed impacts on biodiversity discussed mitigation measures; meaning that most publications assessing impacts of corridors on biodiversity do not propose recommendations to manage the impacts they foresee. When impact mitigation measures are proposed the focus was on minimisation, avoidance or a combination of minimisation and avoidance. The observed stronger emphasis on minimisation suggests that mitigation measures are generally considered in the design or implement stage, despite avoidance being the most reliable strategy for reducing impacts (Phalan et al., 2018; Sonter et al., 2020).

Perhaps one of the most important gaps is that only two publications explicitly mentioned the mitigation hierarchy as a framework to manage impacts—and none used it to explore the achievement of no net loss or net gain for biodiversity. Consequently, there were no studies considering the two last stages of the mitigation hierarchy: restoration and offsetting. Biodiversity offsets or compensation are a particularly important last step to fully applying the mitigation hierarchy framework, and in principle are either already part of development policy or soon will be for a majority of countries in the world (GIBOP, 2020).

Addressing Evidence Gaps

Although there is substantial practical and scientific knowledge on how to manage the impacts on biodiversity from linear infrastructure, this review found little specific application of this knowledge to the specific case of development corridors. Nevertheless, there have been important advances in impact mitigation science in recent years that could be adapted to development corridors. On the one hand, holistic frameworks exist that identify key risks and opportunities for conservation and development, by taking a spatially explicit approach to map biodiversity priorities in relation to predicted impacts. For example, the Development by Design framework (Kiesecker et al., 2010; Tallis et al., 2015) combines the application of the mitigation hierarchy with Systematic Conservation Planning (Margules and Pressey, 2000) to take into account conservation priorities when planning for developments. It has already been applied in several countries, such as Mongolia (Heiner et al., 2019a), India (Kiesecker et al., 2020), and Colombia (Saenz et al., 2013). Similarly, Vilela et al. (2020) take an approach that combines economic and environmental assessments. The environmental and social impacts of 75 road projects in the Amazon were assessed to find that 45% of these will generate economic losses as planned. However, they showed that choosing the right projects and strategies through a multicriteria analyses of positive and negative outcomes, could result in achieving 77% of the economic benefit at 10% of the negative predicted impact. Of paramount importance is to design approaches that consider needs of people in addition to biodiversity. Heiner et al. (2019b) show how development at a landscape level can be planned by using the mitigation hierarchy as a framework to proactively map values and mitigation actions considering synergies and trade-offs between social, cultural and environmental priorities in Australia.

In addition to adopting an holistic framework, it is important to consider the full suite of direct, indirect and cumulative impacts that developments can generate—considering these impacts are likely to be much more severe than only assessing direct impacts (Johnson et al., 2020). For example, Tulloch et al. (2019) used expert opinion and spatial prioritisation analyses to assess the impacts of planned roads, railways and pipelines in southern Australia. They found that the footprint of indirect impacts could be four times higher than only assessing direct impacts. Whitehead et al. (2017) used spatial prioritisation techniques to map cumulative impacts produced by multiple projects. Their approach identified minor alterations to the original development plans that could result in reductions in biodiversity impacts and informed expansion of the protected area network in Western Australia. Recently, data on cumulative impacts at a large scale has been made available. For example, global datasets mapping cumulative pressures in the seas (Halpern and Fujita, 2013; Shackelford et al., 2018) and land

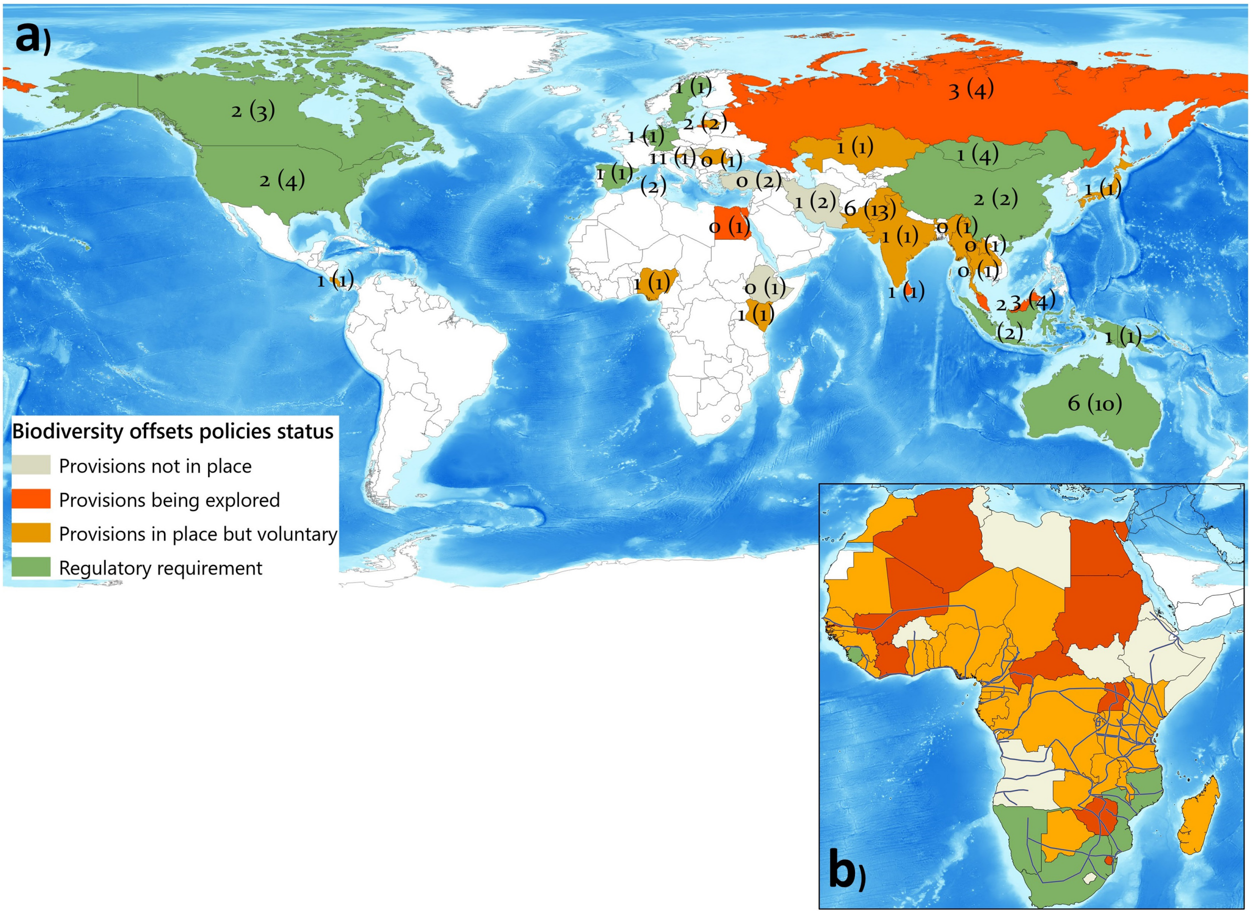

FIGURE 6 | Number of country case studies proposing biodiversity mitigation measures in each country and, between brackets, total of country case studies. Colors indicate the status of national biodiversity offset policies according to the Global Inventory of Biodiversity Offset Policies (GIBOP, 2020), shown for country case studies picked up by our review only. **(a)** Global overview of the results per country of this review. **(b)** Case study for the African continent where blue lines represent 33 ongoing or planned development corridors (Laurance et al., 2015). The map shows that most countries in Africa where development corridors are planned or ongoing have the policy mechanisms in place to pursue better outcomes for biodiversity through ecological compensation.

(Venter et al., 2016; O'Bryan et al., 2020) at one kilometre resolution are available and can further inform strategic impact assessments for development corridors.

Whether development corridors can be designed and implemented to at least achieve no net loss or better for biodiversity remains an unanswered question. In general, achieving no net loss or better for biodiversity is challenging and controversial (Maron et al., 2018), especially in relation to biodiversity offsetting technical implementation (Gardner et al., 2013; zu Ermgassen et al., 2019a) and governance (Damiens et al., 2021). Sonter et al. (2020) modelled the achievement of no net loss under 18 different national policy settings in Brazil, Australia, Indonesia, and Mozambique and found that no policy achieves no net loss for biodiversity in any of the scenarios they modelled. They conclude that avoidance is the most important action to achieve no net loss goals. Similar approaches of participatory scenario planning could be applied to development corridors to identify where the environmental impacts can more effectively be mitigated and understand potential effects of specific policies on achieving a no net loss goal. Similarly, target-based ecological compensation has been proposed to overcome offset challenges (Simmonds et al., 2019). Novel approaches are being explored to encourage proactive conservation actions across all sectors of society building from the mitigation hierarchy (Milner-Gulland et al., 2021). None of these have been yet considered for development corridors.

Policy Implications

No net loss or net gain goals are not only becoming increasingly mainstream for industry but also in global and national policies. Achieving positive outcomes for biodiversity and ecosystem services will likely be a critical component of the post-2020 global biodiversity framework of the Convention on Biological Diversity. In this context, Díaz et al. (2020) propose a strict no net loss goal as a highly ambitious end point that can only be achieved through a coordinated and holistic approach that considers socio-economic and environmental trade-offs.

Notwithstanding the challenges to achieve no net loss, the policies under which it could be pursued for development corridors already exist in some countries where they are ongoing or planned (**Figure 6**). The Global Inventory on Biodiversity Offset Policies (GIBOP), which summarises the degree to which biodiversity compensation policies and the mitigation hierarchy are embedded within national environmental policy frameworks, shows that 100 countries have or are developing biodiversity compensation and/or offset policies (Bull and Strange, 2018).

According to GIBOP, 36% of our initial 45 countries already have regulatory requirements for offsets for at least some projects in some circumstances, 38% provide guidance or have measures in place to facilitate voluntary offsetting (GIBOP, 2020), and 13% have no provisions could be found with regards to compensation/offset (**Figure 6**). In Africa, we know that at least 33 development corridors are or will be dissecting the continent in the next decades (Laurance et al., 2015). Yet, only three country case studies and four regional studies in Africa assessed impacts on biodiversity and proposed mitigation measures but none proposed the use of offsets despite most countries having voluntary or compulsory provisions already in place (**Figure 6b**). It seems urgent and necessary that future impact assessment of development corridors in peer reviewed literature consider not only best practice but also existing compulsory or voluntary policy guidance on impact mitigation at a national level.

Tools for impact assessment, such as EIA and SEA could be the conduit through which best practice and regulatory requirements are implemented at a national level. SEAs seem particularly well-suited to do this as SEAs necessarily involve stakeholders coming together to assess environmental, social, and economic risks and alternatives to development at policy, planning and programming levels. This approach is critical for responding to the transboundary nature of development corridors, while ensuring these align with broad sustainability strategies and national policies. Still, in our review only one publication focused on developing methods to improve SEAs outcomes (Ramachandran and Linde, 2011). Similarly, lessons learned from jurisdictional approaches to REDD+ (i.e., reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks) could provide some insights into how to achieve positive outcomes from initiatives that comprise multiple projects across a landscape. Jurisdictional approaches to REDD+ were taken acknowledging that significant reductions in deforestation could not be achieved by individual projects and that success in protecting forests and climate relied on successful implementation government-led policies and programs at multiple levels (Boyd et al., 2018).

CONCLUSION AND FURTHER RESEARCH

Our review compiled 271 articles from across all continents, 189 country level and 82 transnational case studies, confirming development corridors are a globally widespread phenomenon. We find that, for the specific case of development corridors, impact mitigation in peer reviewed literature does not give sufficient consideration to biodiversity impact mitigation following best practice and there is a lack of an integrated approach that considers the whole suite of potential economic, environmental and social impacts of these complex multi-project and multi-stakeholder initiatives. While impacts of development corridors on biodiversity have been assessed to some extent, there is little research focusing on testing different alternative configurations to minimise losses and maximise opportunities. Moreover, assessment of impacts on ecosystem services seems almost absent in the literature, which is problematic if development corridors are to deliver sustainable development. We argue that research needs to be scaled up and learn from other advances in impact mitigation science to assess and quantify direct, indirect and cumulative impacts on biodiversity and ecosystem services, apply the mitigation hierarchy in full and consider synergies and trade-offs in a spatially explicit way. SEAs seem like an appropriate framework to integrate these approaches into a better impact assessment process.

Given the direction global and national policy, industry and civic society are taking in pursuing positive outcomes for biodiversity from human development, as explained in this review, development corridors design and implementation need to explore at least the viability of no net loss. There are policies and methodological approaches available that can be adapted to assess the technical feasibility and policy conditions needed for doing this. We do not know whether current development corridors are achieving the social and economic objectives they set out for, but we are confident that the numerous risks they pose to biodiversity and ecosystem services have not been sufficiently addressed to date.

AUTHOR CONTRIBUTIONS

DJ-B carried out the research, the analyses, created the tables and figures, and wrote the first draft of the manuscript. JB supervised the research. JB, RS, NB, and JH contributed to the design of the research and commented on early drafts of the manuscript. JB, NB, JH, RS, CT, and JT reviewed and edited the manuscript significantly contributing to the final version. All authors contributed to the article and approved the submitted version.

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